

SUBJECT: Space Tug Operational Requirements
for Satellite Placement, Revisit
and Retrieval - Case 105-6

DATE: July 29, 1970

FROM: M. H. Skeer

ABSTRACT

A presentation entitled "Space Tug Operational Requirements for Satellite Placement, Revisit, and Retrieval" was given at the Symposium on Chemical Orbit-to-Orbit Shuttles, held at Langley Research Center on June 23-24, 1970. This memorandum recounts some of the principal points addressed in the presentation.

The interaction of the space tug with other Integrated Program hardware is explored to gain an appreciation of the relative merits of possible operational modes. These modes include 1) ground based, utilizing the space shuttle only, and the shuttle and tug; and 2) space based, utilizing the tug at the space station (or at a propellant facility separate from the space station). In ensuing discussion, regions of the sky accessible with each mode are considered; and then the relationships of the different modes with respect to one another are viewed. The nature and complexity of operational tradeoffs involved and their potential impact on Tug sizing are in course examined. Several of the view-graphs contain data not covered in previous memoranda and are dwelt upon in relatively greater detail.

It is noted that selection of operational modes is perhaps as significant as selection of space tug size and design configuration. Acceptance of complex modes can enable considerable reduction in tug size and simplification of design (through relaxed weight constraints). Moreover it is not clear that either space based or ground based operations are preferable throughout the complete spectrum of missions. Both may have a role in selected regions of the sky.

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MEMORANDUM FOR FILE

A presentation by the author entitled "Space Tug Operational Requirements for Satellite Placement, Revisit, and Retrieval" was given at the Symposium on Chemical Orbit-to-Orbit Shuttles (Reference 1), held at Langley Research Center on June 23-24, 1970. The viewgraphs are contained in the attachment. This memorandum discusses some of the principal points addressed in the presentation. Several of the viewgraphs contain data not covered in previous memorandum and are dwelt upon in relatively greater detail.

The satellite placement and retrieval problem is reduceable to several component problems

- Spatial distribution of satellites, and
- Transportation to and from satellite orbits.

The present discussion considers only the transportation issue. The interaction of the Space Tug with other Integrated Program hardware is explored to gain an appreciation of the relative merits of possible operational modes. No attempt is made to draw conclusions; rather this discussion examines the nature and complexity of operational tradeoffs involved and their potential impact on Tug sizing and required propellant fraction.

Figure 1

The tug is viewed first in the context of total program requirements (Reference 2). The tug is to fulfill requirements in earth orbit, lunar, and planetary mission areas. The earth orbit mission area is currently deemed first in order of priority. Satellite placement, revisit and retrieval missions are the most demanding earth orbit missions in terms of required stage performance. Other

missions in earth orbit require relatively low velocity changes. Requirements of lunar and planetary mission areas tend to degrade stage performance by increasing stage weight.

Figure 2

The following chart summarizes means by which satellite placement and retrieval operation could be performed; either from the ground via 1) space shuttle only or 2) space shuttle and tug; or on-orbit via the tug in association with a space station or propellant loading facility. Ground based launch provides direct access to all inclinations above 28.5° via all azimuth launch. On-orbit, operations are presumed to initiate from a space station at 270 nm altitude, 55° inclination so that other inclinations would be accessible only by plane change. Propellant facilities or refueling by the space shuttle at higher or lower inclinations would be required to enable more complete sky coverage to be achieved.

In ensuing discussion, regions of the sky available to each hardware element combination are considered; and then the relationships of the different hardware combinations with respect to one another are viewed.

Figure 3

Estimated payload capability of the space shuttle to various altitude and inclinations (Reference 3) is shown in the next figure. Cases for nominal payload sizes of 25,000 lbs and 50,000 lbs are given, where nominal payload is specified to be round trip payload to and from a space station at 270 nm altitude and 55° inclination. Note that the maximum altitude that can be reached at low inclination is on the order of 1000 nm and that the payload to a given altitude decreases significantly at higher inclinations. The maximum payload delivered to orbit at a specified inclination is determined by the payload to minimum altitude, at approximately 100 nm. Note that at 100 nm altitude, 28.5° inclination the 25,000 lb shuttle can deliver a maximum of 50,000 lbs and the 50,000 lb shuttle can deliver 80,000 lbs. For lower inclinations the shuttle must provide plane change and payload diminishes rapidly.

In the ensuing discussion, the 25,000 lb shuttle is presumed since performance sensitivity for operations in association with the space tug is greater, and operations with the tug are more constrained, underscoring the operational tradeoffs involved.

Figure 4

Ground based operations utilizing the space shuttle and space tug are considered next. The figure illustrates regions of accessibility over the range of altitudes and inclinations for a representative set of hardware and payload. A 25,000 lb shuttle, 50,000 lb tug and 10,000 lb discretionary payload are assumed. The 50,000 tug corresponds to the maximum payload the 25,000 lb shuttle can deliver to orbit (at 100 nm, 28° inclination). For higher inclinations the tug is off-loaded such that propellant available is equal to shuttle payload to 100 nm minus tug dry weight and discretionary payload. A specific impulse, I_{sp} , of 460 sec and propellant fraction (λ) of .88 are assumed for the tug. (It is noted that the performance figures are relatively optimistic.) The three curves indicate regions of accessibility for 10,000 lb payload placement and 10,000 lb payload retrieval for the shuttle and tug and for comparison, payload placement using the shuttle only.

A brief description of the regions of accessibility can provide some basic insight into the complexity of the tradeoffs involved. Consider first the payload placement case:

- Maximum altitude is achieved at 28.5° inclination.
- In the region from 0° - 28.5° inclination accessibility is achieved by tug plane change, since the shuttle cannot reach these inclinations directly. As a consequence achievable altitude falls off rapidly.
- In the region from 28.5° to about 90° inclination, direct launch is achievable and accessible altitude falls off relatively slowly. Through this region, a complex tradeoff exists between, 1) direct injection, and 2) shuttle launch to reduced inclination accompanied by tug plane change to the desired inclinations. This effect becomes a dominant factor for inclinations between 70° and 90° and is approximately incorporated in this range.

- In the region above 90° inclination, shuttle payload to 100 nm is so reduced that plane change by the tug is required and payload falls off rapidly. This region is important in that it encompasses sun-synchronous orbits.

The situation is somewhat altered for satellite retrieval. It would intuitively be expected that satellite placement would be easier than retrieval, from a performance standpoint, since growth factor sensitivity (gross weight per pound of payload for a given roundtrip mission velocity) is substantially less. However, in the payload retrieval case considerably more tug propellant is available as the discretionary payload is not launched from ground. For the large 10,000 lb payload the greater propellant supply in the retrieval case offsets the increased growth factor sensitivity, and at inclinations under 60° performance for payload placement and retrieval are almost identical. At higher inclinations the propellant available for payload retrieval enables direct shuttle launch to be achieved to inclinations in excess of 120° and altitudes in excess of 400 nm. Consider a brief example to demonstrate this point:

At 60° inclination shuttle payload to 100 nm = ~40,000 lbs

	<u>Placement</u>	<u>Retrieval</u>
Shuttle payload	40,000 lbs	40,000 lbs
Less: Tug dry weight	6,000	6,000
Less: Discretionary payload	10,000	-----
Propellant Available	24,000 lbs	34,000 lbs
Roundtrip ΔV Available for Tug	9,250 fps	9,650 fps

At 100° inclination shuttle payload to 100 nm = 20,000 lbs

	<u>Placement</u>	<u>Retrieval</u>
Shuttle payload	20,000 lbs	20,000 lbs
Less: Tug dry weight	6,000	6,000
Less: Discretionary payload	10,000	-----
Propellant Available	4,000 lbs	14,000 lbs
ΔV available	2,200 fps	5,700 fps

The tradeoff between placement and retrieval would be substantially modified for smaller payloads where offloading is less significant.

Figure 5

Consider next space based operations in association with a space station. Orbits precess as a function of their altitude and inclination; thus relative precession of the lines of nodes between the space station and satellite orbits usually results. The transfer velocity between orbits has an associated time relationship which is dependent on the phasing of the orbits (as indicated for three representative orbits). Satellite placement is not significantly affected by this phasing relationship since placement is usually independent of the location of the line of nodes* and minimum transfer velocities to the orbit is utilized. However, satellite revisit and retrieval would be subject to such operational constraints and it would be necessary to accommodate the phasing problem. In the event of satellite failure, for example, either a spare would have to be available, the extended downtime would have to be accepted, or some form of high energy maneuver such as tug staging would have to be employed. It may be noted that slight separation in orbits (low minimum transfer ΔV) results in low relative precession rates and long phasing periods (few minimum ΔV transfer opportunities), whereas orbits with large separation (high minimum transfer ΔV) experience high relative precession rates and therefore short phasing periods (many minimum ΔV transfer opportunities).

Figure 6

Low altitude circular orbits accessible from the nominal 270 nm, 55° inclination space station orbit (Reference 4) are shown for various ΔV 's. Note that plane change to accommodate nodal separation is extremely expensive; for a plane change of less than 30°, a velocity change of 10,000 fps is required. (For a recoverable system twice the velocity would of course be needed.) The maximum range of inclinations that are available can be determined for the various ΔV 's when nodal separation is zero. For example with 10,000 fps each way, inclinations from 30° to 80° are accessible (at some time). The period of accessibility would be a function of the relative precession rate between orbits.

*An important exception are sun-synchronous orbits where the location of the line of nodes is selected to achieve desired lighting conditions.

Figure 7

Tug staging could enable extremely high roundtrip velocities to be achieved for large altitude and inclination (or nodal alignment) changes. Three possible transportation modes are shown (Reference 2). Mode I is a simple roundtrip between a departure orbit and the final orbit. Departure orbit could be either from the Space Station orbit, the space shuttle, or a propellant depot. The final orbit could be any low or high altitude earth orbit, or lunar orbit. In Mode II stage one carries Stage II and payload to an intermediate orbit and returns to the departure orbit. Stage II proceeds to the final orbit with payload and also returns. Mode III is a perturbation of Mode II whereby the second stage is returned to an intermediate parking orbit and retrieved by the first stage which is refueled. The retrieval could be achieved as part of the same mission sequence or on a subsequent mission.

Figure 8

Performance that is achievable by use of these modes is illustrated by the next chart which indicates stage growth factors for roundtrip payloads. As an example, using Mode II a 5,000 lb payload can be delivered roundtrip to geosynchronous orbit from the nominal space station orbit using two 50,000 lb tugs with a λ of .85. Using Mode III (two tugs and three fuel loads) a 10,000 lb payload can be delivered roundtrip to geosynchronous orbit.

Figure 9

Recalling the velocity-time dependency factor governing space based operations, Modes I, II, and III can be used to deliver a small (1,000 lb) manipulator payload to low inclination, geosynchronous, and sun-synchronous orbits respectively. Note that only one minimum ΔV opportunity per year is available for the low inclination orbit whereas five minimum opportunities are available for sun-synchronous orbit. The geosynchronous orbit would be continuously available because the orbit does not precess.

Figure 10

Now that space based and ground based operations have been discussed separately, the interaction of the various modes, and how they might complement each other can be considered. Regions of accessibility are shown for space shuttle only, space tug in association with the shuttle, and space tug in association with the space station. Again, a 25,000 lb space shuttle and 50,000 lb tug (Isp = 460 sec, $\lambda = .88$) are selected. A 5000 lb payload placed in orbit is presumed for this example. It was assumed that the tug would be off loaded to utilize the full payload capability of the shuttle when operating in the ground based mode, but would be fully loaded when operating from the space station. Although this would not result in a direct comparison on the basis of an equal number of space shuttle flights (since more than one shuttle flight would be required to deliver a full propellant load for the tug operating from the space station) it does enable a comparison of missions of equal complexity; that is, a single tug flight.

A comparison of the regions of accessibility shows that there is considerable overlap between space based and ground based modes. Geosynchronous orbit is not accessible in any mode (with a 5000 lb payload); sun-synchronous orbits in excess of 1000 nm are accessible by the tug and shuttle, and low sun-synchronous orbits are accessible by the shuttle only. The curves diverge at high altitudes because escape velocity is achieved.

Figure 11

The next chart shows a similar arrangement, but for 5000 lb payload retrieval in lieu of 5000 lb payload placement. Time becomes an important factor for payload retrieval for operations in association with the space station. An addition to the figure has been introduced to incorporate this consideration. The dashed lines show the locus of orbits of constant relative precession with respect to the space station (which incidently has an absolute precession rate of 4.5%/day). These lines are labeled according to the number of opportunities per year that would be available for retrieval or revisit. Note that a family of orbits exists in which satellites would always be available if nodal alignments were close to that of the space station. Otherwise, these orbits would never be accessible (i.e., if nodal separation was initially too great). This family of orbits has no relative precession with respect to the space station and hence would be of extreme importance for placement of satellites requiring frequent servicing and repair.

The region of accessibility from the space station is completely encompassed by the region accessible from the shuttle and tug. Again geosynchronous and sun-synchronous orbits are not accessible from the station but sun-synchronous orbits would be accessible by the tug/shuttle combination.

Figure 12

Geosynchronous orbit presents a particularly difficult problem in all modes utilizing a single tug. The final chart indicates why. Stage growth factors are given as a function of λ for representative specific impulses. Payload placement, retrieval, and roundtrip cases are shown. A λ of about .86 is the lower threshold for achieving geosynchronous orbit with small payloads. Below $\lambda = .88$ sensitivity to λ and Isp is extremely high and a λ of at least .90 is necessary to achieve retrieval missions. The roundtrip missions are extremely expensive for representative payloads of between 5,000 and 10,000 lbs. To deliver a 10,000 lb payload or retrieve a 5,000 lb payload would require a tug of about 80,000 lbs with a λ of .90. Such a tug would only be compatible with the large 50,000 lb space shuttle so that the shuttle characteristics looms as a primary constraint for performing such geosynchronous missions. Tug staging with small tugs of 50,000 lbs and $\lambda = .85$ can, however, enable these missions to be achieved from the space station with considerable margin to spare.

In summary, selection of operational modes is perhaps as significant as selection of space tug size and design configuration. Acceptance of complex modes can enable considerable simplification of design. Moreover it is not clear that either space based or ground based operations are preferable throughout the spectrum of missions. Both may have a role in selected regions of the sky.



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1013-MHS-klm

Attachments
Figures 1-12

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REFERENCES

1. Cassidy, D. E., and M. H. Skeer, "Mini"-Symposium on the Chemical Orbit-to-Orbit Shuttle, Langley Research Center," July 9, 1970.
2. Skeer, M. H., "Space Tug Operations in Association with the Integrated Program," Bellcomm Memorandum for File, January 9, 1970.
3. Cassidy, D. E., "Estimated Space Shuttle Capability in Support of Unmanned Payloads," Bellcomm Memorandum for File, April 21, 1970.
4. Bosch, H. B., "Transfer Velocities Between Earth Space Stations and Satellites," Bellcomm Memorandum for File, November 24, 1969.

SYSTEM COMMONALITY

MISSION AREA	OPERATIONS
EARTH ORBIT	<ul style="list-style-type: none"> ● SPACE BASE SUPPORT ACTIVITIES <ul style="list-style-type: none"> ● SPACE BASE ASSEMBLY ● TRANSFER PAYLOADS FROM SS AND NUCLEAR SHUTTLE ● ORBIT KEEPING ● INSPECTION ● SATELLITE PLACEMENT AND RETRIEVAL ● IN SITU SATELLITE SERVICING AND INSPECTION ● SATELLITE AND INTERPLANETARY SPACECRAFT LAUNCH ● CREW SHUTTLE TO SYNCHRONOUS ORBIT
LUNAR	<ul style="list-style-type: none"> ● LUNAR SURFACE TO ORBIT CREW TRANSFER ● DELIVERY OF LUNAR SURFACE BASE AND OTHER SURFACE PAYLOADS ● SATURN V 4th STAGE ● RESCUE ● TUG CAPSULE AS SHORT TERM BASE ON SURFACE
PLANETARY	<ul style="list-style-type: none"> ● MIDCOURSE CORRECTION MANEUVERS ● PLANETARY ESCAPE AND EARTH CAPTURE MANEUVERS ● RESCUE (DUAL SPACECRAFT MODE)

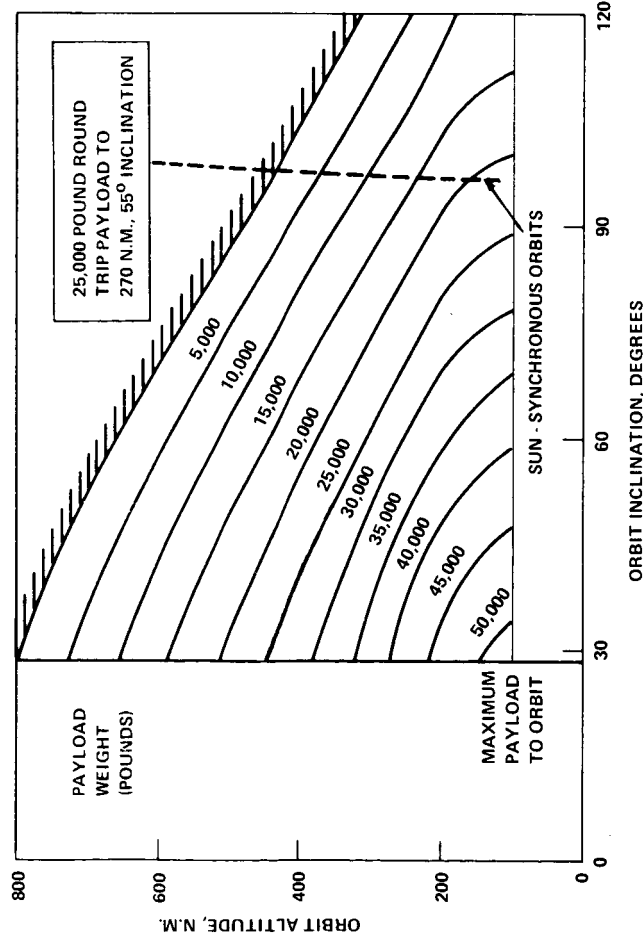
FIGURE 1

OPERATIONAL MODES

- GROUND BASED
 - SHUTTLE ONLY
 - SHUTTLE AND TUG
- SPACED BASED
 - TUG AT SPACE STATION
 - TUG AT PROPELLANT FACILITY
(SEPARATE FROM SPACE STATION)

FIGURE 2

ESTIMATED PAYLOAD ONE-WAY CAPABILITY OF A 25,000 POUND
PAYLOAD SPACE SHUTTLE - DIRECT INJECTION, DIRECT DEORBIT



ESTIMATED PAYLOAD ONE-WAY CAPABILITY OF A 50,000 POUND
PAYLOAD SPACE SHUTTLE - DIRECT INJECTION, DIRECT DEORBIT

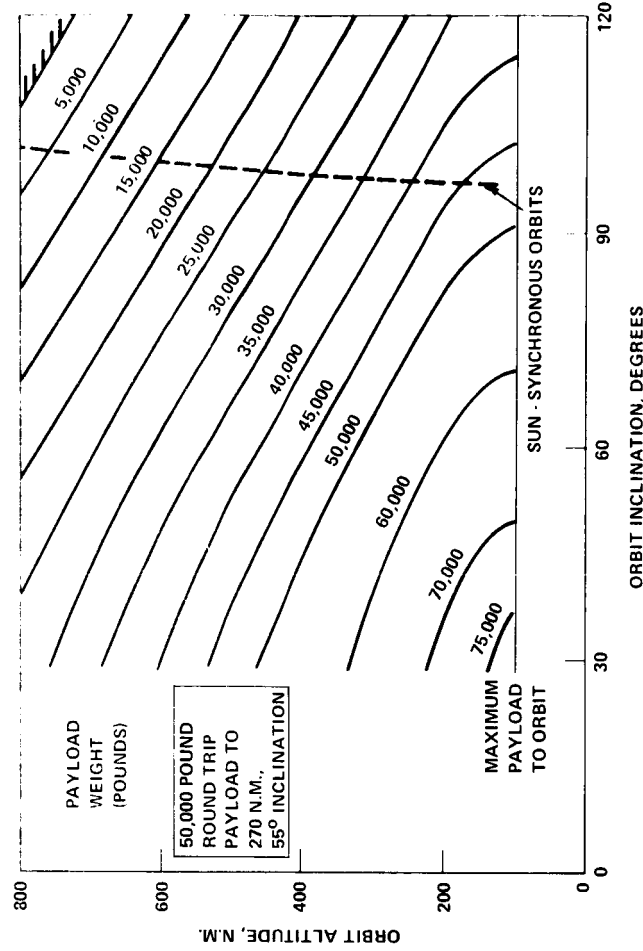


FIGURE 3

REGIONS OF ACCESSIBILITY FOR SPACE TUG/SPACE SHUTTLE DELIVERY AND RETRIEVAL

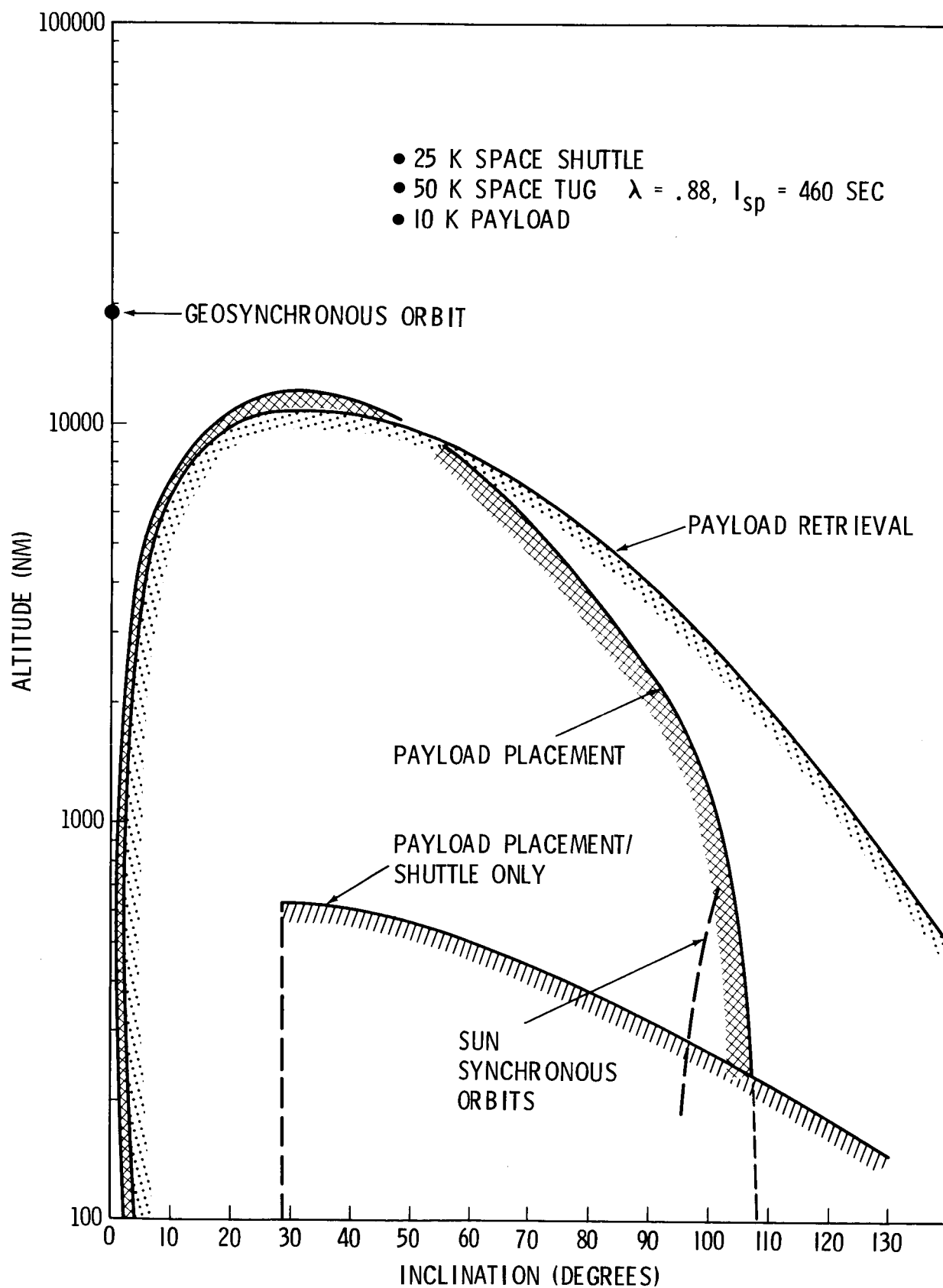


FIGURE 4

ONEWAY TRANSFER VELOCITY FROM A SPACE STATION @ 250 NM; ALTITUDE 55° INCLINATION

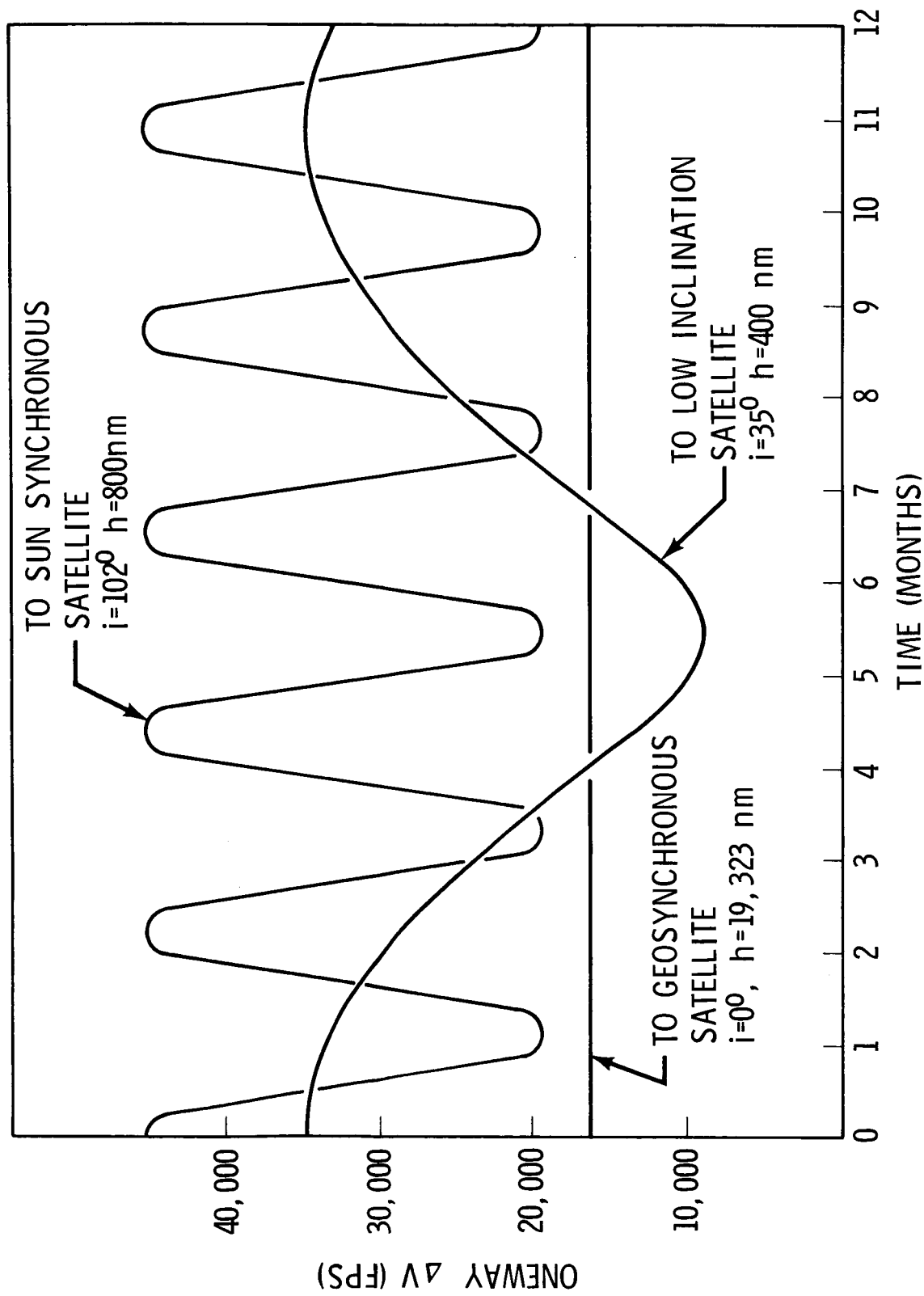


FIGURE 5

CIRCULAR ORBITS ACCESSIBLE FROM 250 nm, 55° INCLINATION SPACE STATION

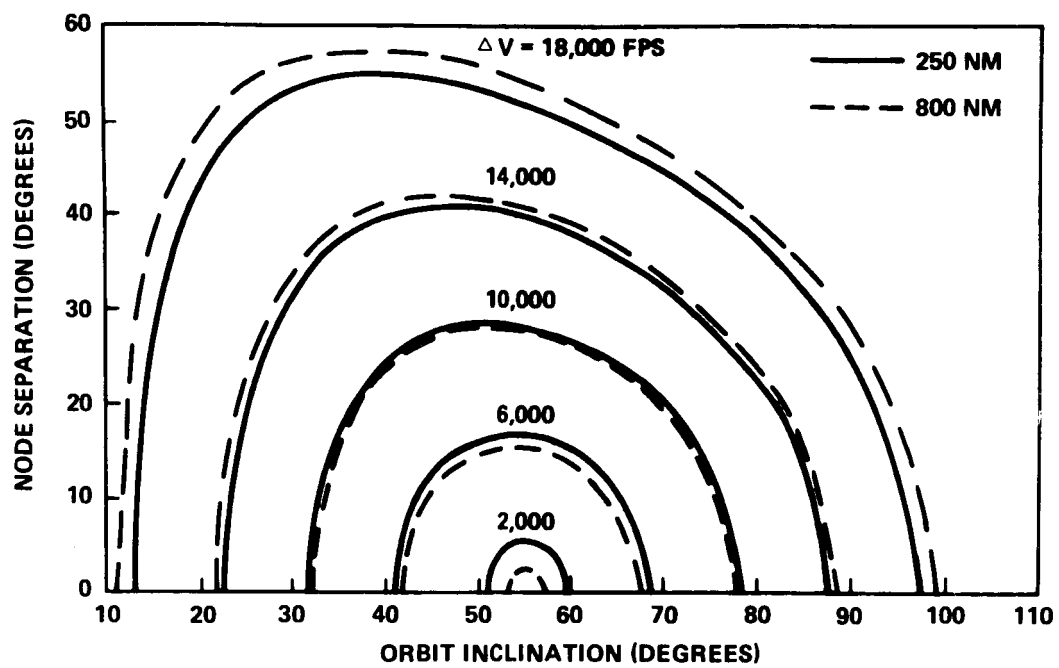


FIGURE 6

TUG STAGING MODES

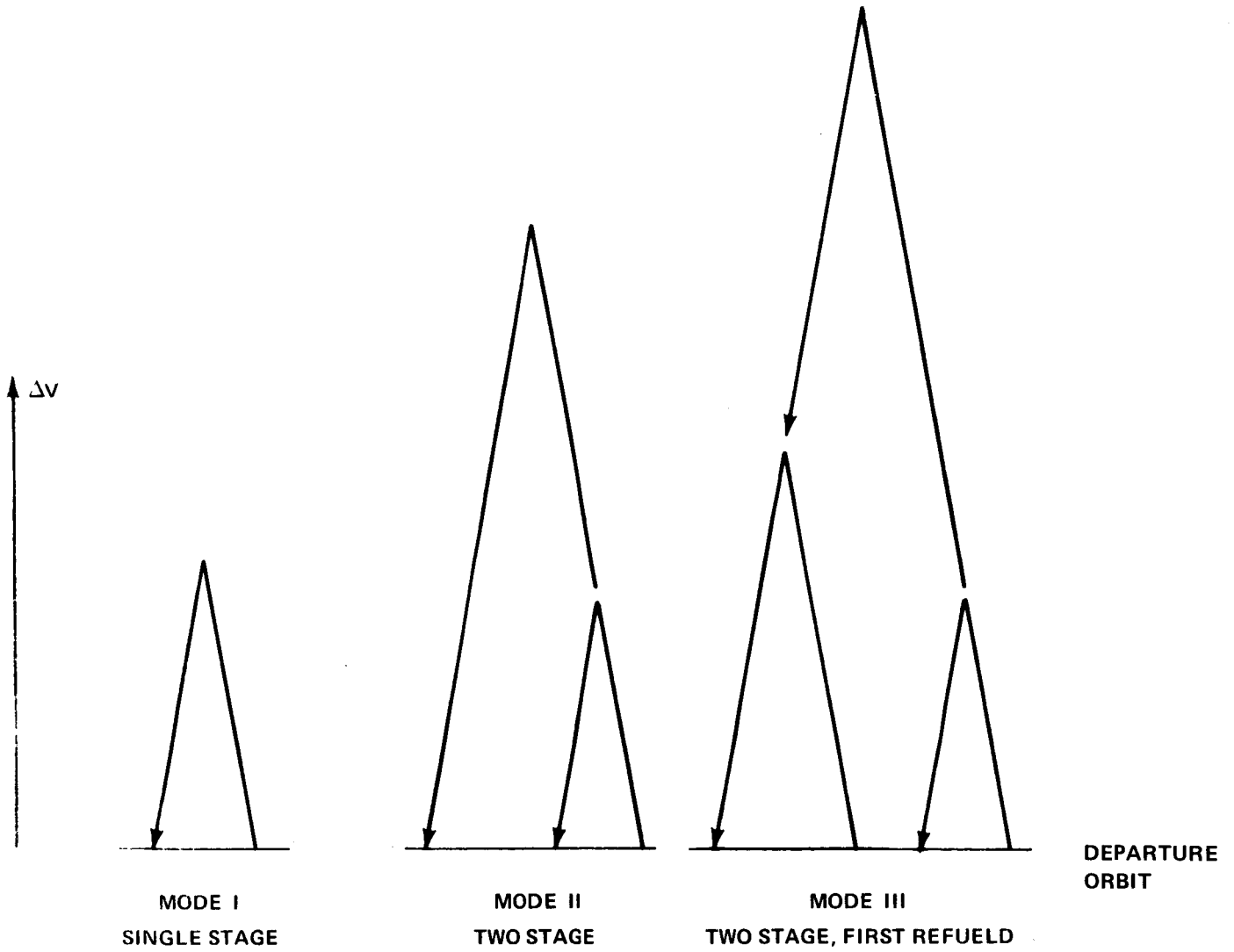
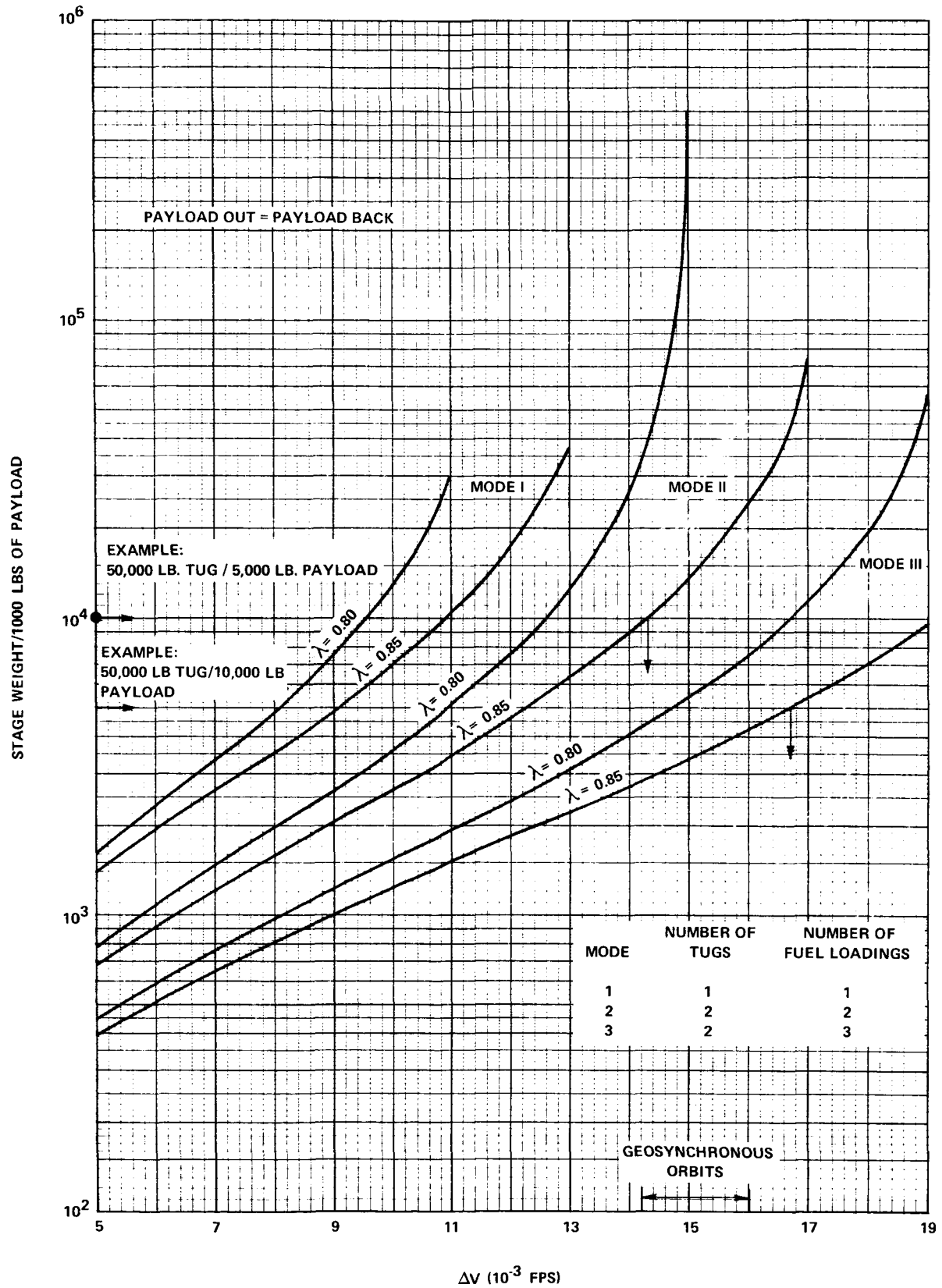


FIGURE 7

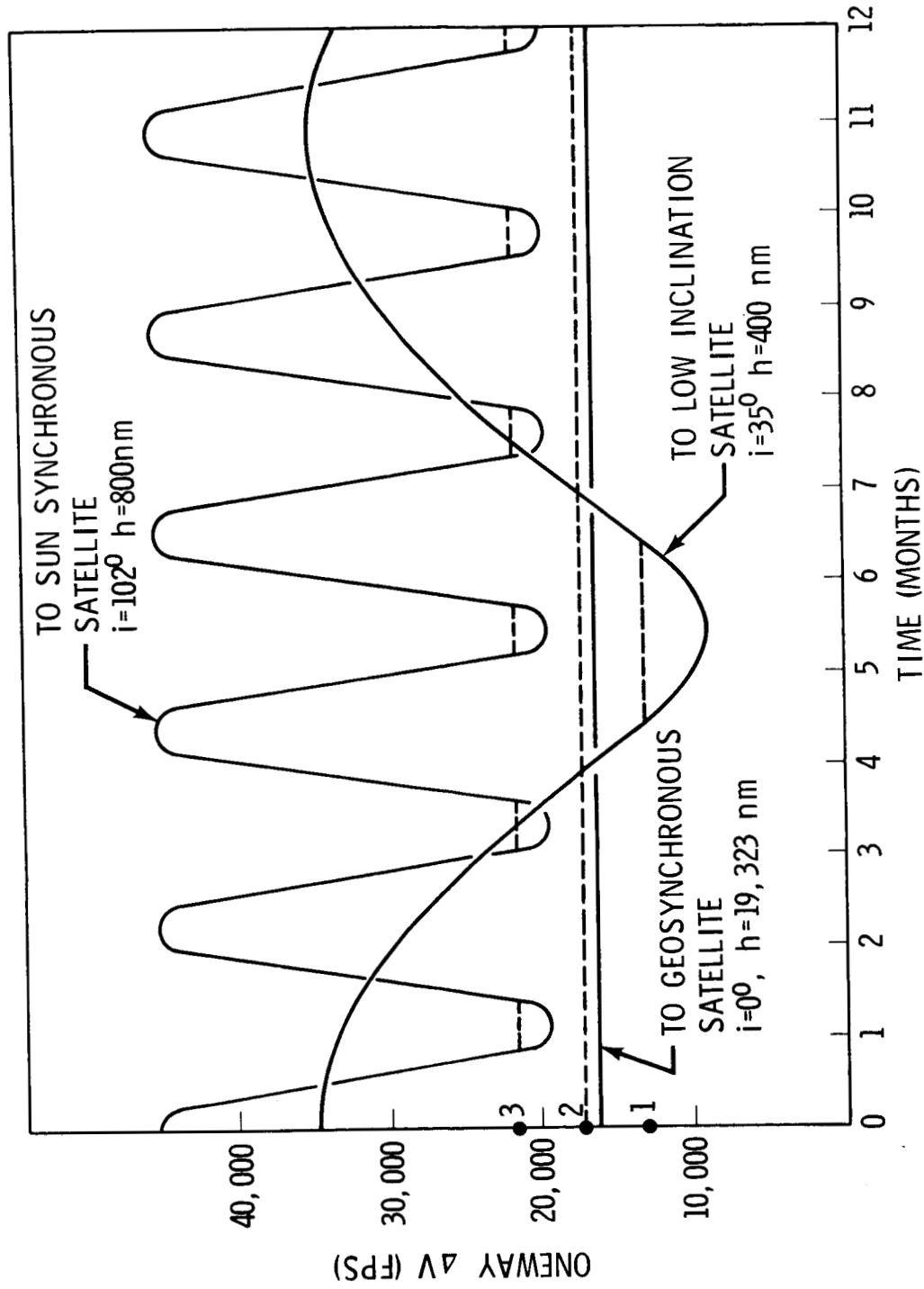
SPACE TUG GROWTH FACTORS FOR ROUND TRIP PAYLOAD
(ALL STAGES RECOVERABLE)



ΔV (10^{-3} FPS)

FIGURE 8

ONEWAY TRANSFER VELOCITY FROM A SPACE STATION @ 250 NMi ALTITUDE 55° INCLINATION



NOTE: CAPABILITIES OF 50 K SPACE TUG WITH MANIPULATOR

- 1) SINGLE TUG
- 2) STAGED TUGS (2 FUEL LOADINGS)
- 3) STAGED TUGS (3 FUEL LOADINGS)

FIGURE 9

REGIONS OF ACCESSIBILITY FOR VARIOUS EARTH ORBIT TRANSPORTATION SYSTEMS

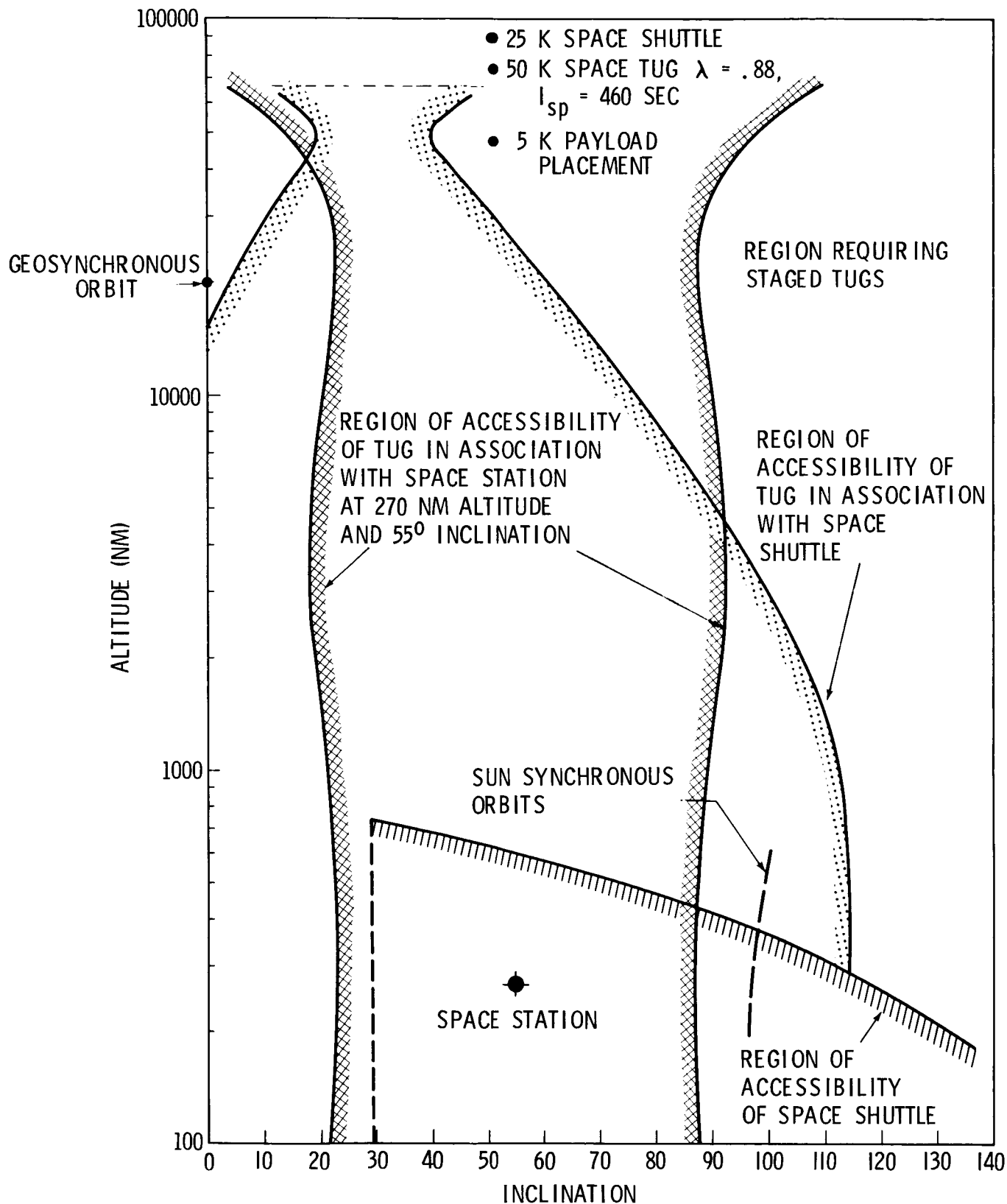


FIGURE 10

REGIONS OF ACCESSIBILITY FOR VARIOUS EARTH ORBIT TRANSPORTATION SYSTEMS

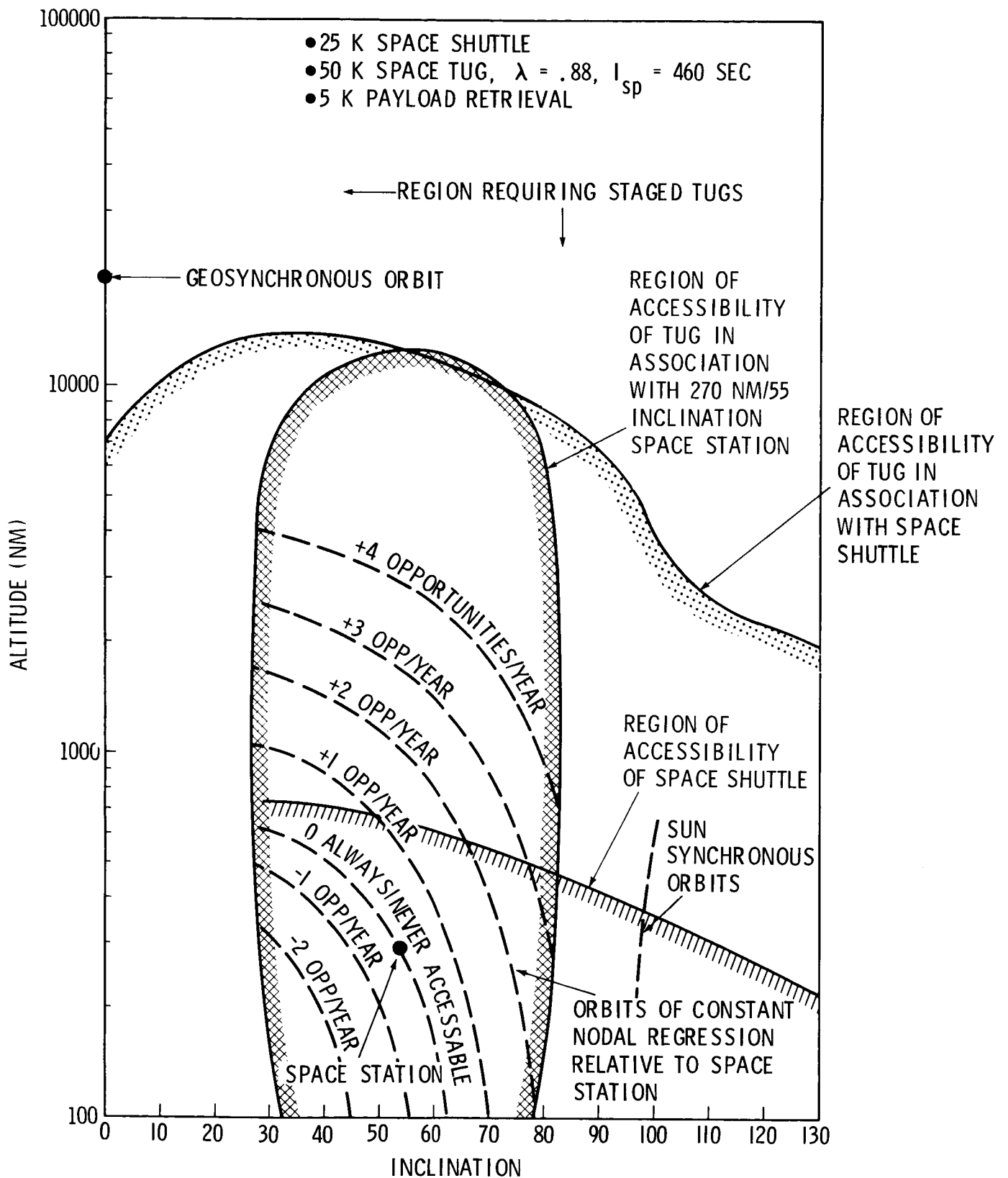


FIGURE 11

SPACE TUG CAPABILITY FOR PAYLOAD DELIVERY AND RETRIEVAL TO AND FROM SYNCHRONOUS ORBIT

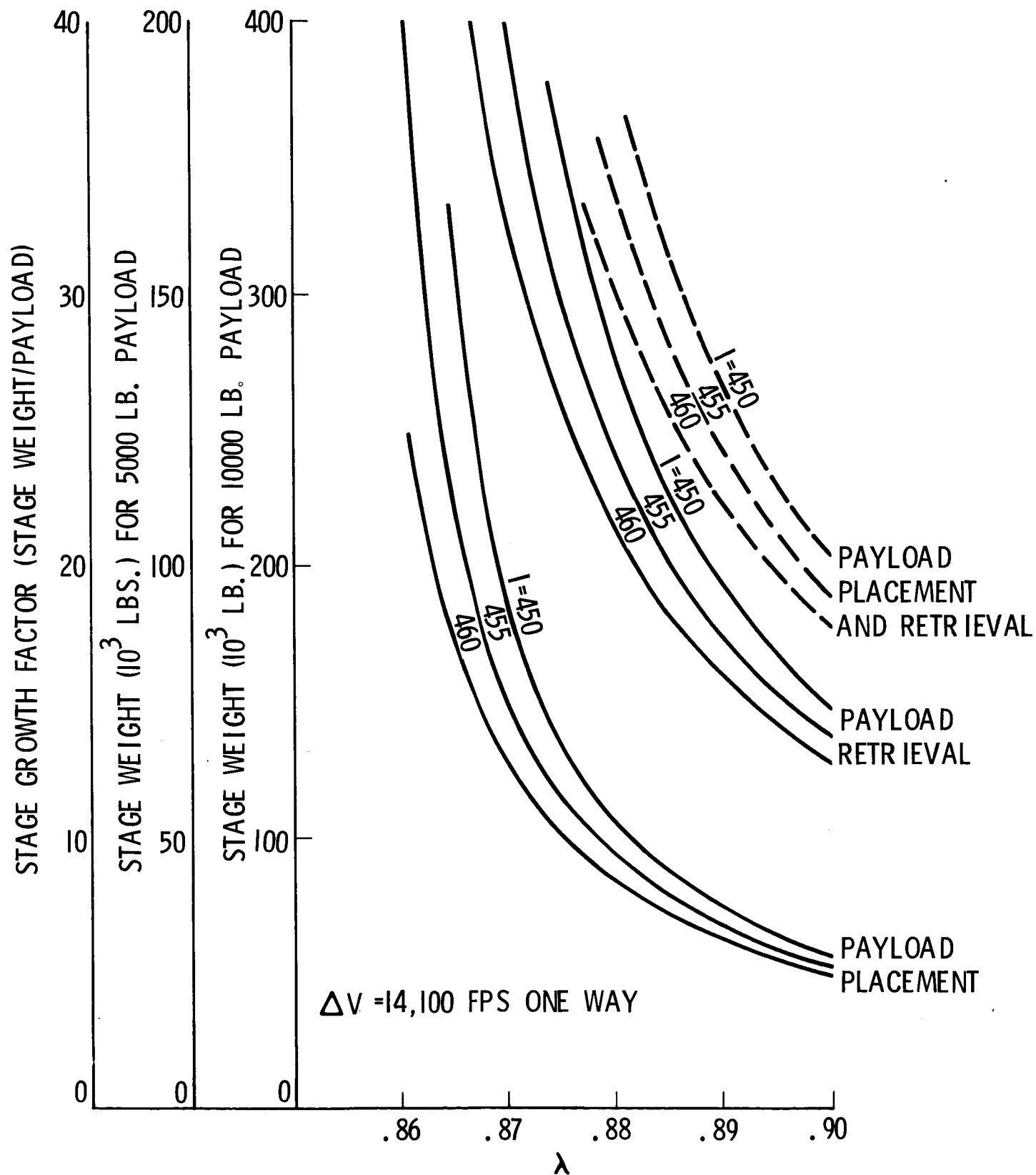


FIGURE 12